Revisiting history: Can shipping achieve a second socio-technical transition for carbon emissions reduction?

Abstract

This paper draws on socio-technical transitions theory to contextualise recent developments in the technological and operational eco-efficiency of ships, which may ameliorate but not resolve sustainability challenges in shipping. Taking an historical perspective, the paper argues that shipping is fundamentally a derived demand arising out of, but also enabling, the spatial separation of production and consumption that are integrated through global value chains. It is argued that the twin processes of innovation-enabled specialisation (into e.g. container ships; bulk carriers etc.) and increased scale both of ships and of shipping operations have embedded shipping into logistics systems of increasing complexity and reach. The objective of the paper is to demonstrate, using secondary data, the long-run trends in the growth of shipping carbon emissions for bulkers and tankers, as well as the impact of increased scale and vessel speed on such emissions. A fuel-based, top-down, methodology, based on fuel consumption estimates derived from secondary source industry data that are suitable for a macro-level analysis, is used to estimate global shipping carbon emissions. It is argued that technologies or operational innovations that reduce the environmental burdens of shipping, while useful, do not represent the socio-technical system 'regime' shift that international maritime logistics requires in order to contribute to improved sustainability. Rather, in the relative absence of strong governance mechanisms in the maritime field, it is underlying 'landscape' shifts in production and consumption that are likely to act to reduce the demand for shipping and hence to be more significant in the longer run.

Keywords

Socio-technical transitions; shipping; eco-efficiency; multi-level perspective; technological innovation; governance.

1. Introduction

The purpose of this paper is to investigate whether technological and operational innovations in shipping will result in a substantial and swift reduction in carbon emissions, and herald the emergence of a new socio-technical regime in shipping. Rather than seeking to forecast outcomes, the paper considers historical change to date to argue that profound path dependency alongside further shipping volume growth is likely to overwhelm eco-efficiency measures.

There is a robust stream of scholarship on the ways in which technological innovations permeate economic and social life to become embedded as dynamic, self-reproducing structures, encompassing markets, products, regulatory frameworks, practices, and behaviours. Recent research in this area stems from pioneering studies on shipping, and the transition from sail to steam (Geels, 2002). Increasingly, those interested in socio-technical transitions are turning from historical studies to more policy-orientated endeavours to promote sustainability - and one area of interest is transport (Geels, 2005; 2012; Fallde and Eklund, 2015; Upham et al., 2015).

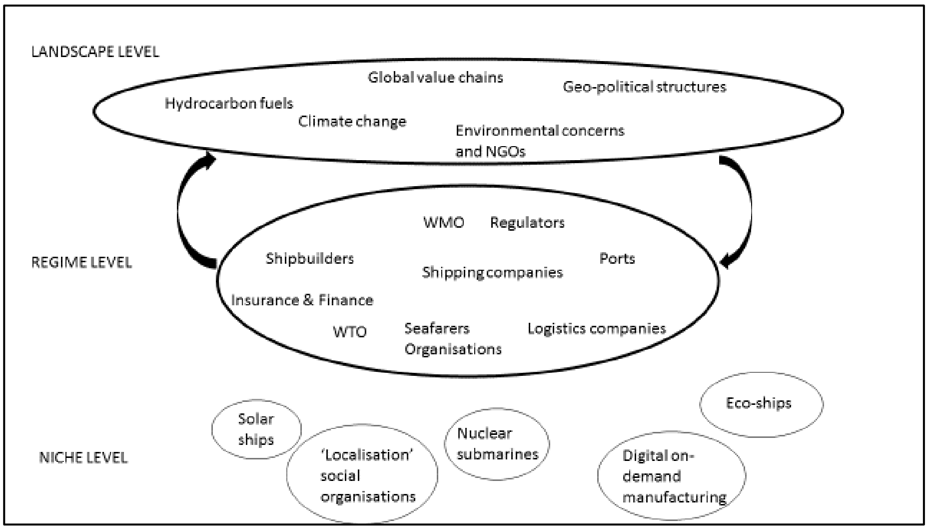
It is expected that when shipping is observed over time it will have become more embedded in global production systems as a result of, and by virtue of its contribution to, the spatial separation of supply and demand. It is further expected that the combination of path dependency and fragmented governance structures in shipping will have acted to reduce the scope for socio-technical developments at a 'niche' level, and the impact of eco-efficiency measures. Consequently, the working hypothesis underpinning this discussion is that, unlike other transport realms within which sustainable socio-technical transitions interventions may be achieved, the global shipping industry is far more likely to be immune to the usual prescriptions of this theoretical perspective.

In section 2, socio-technical transitions theory is discussed and relevant literature in the transport realm, where the connection to climate change has long been recognised, is reviewed (Chapman, 2007). Section 3 summarises sustainability issues associated with shipping, with a focus on carbon emissions growth using bulk and oil tankers as illustrative examples. The argument presented in section 4 is that the processes of innovation-enabled specialisation (into, for example, container ships; bulk carriers; oil tankers), standardisation, and operational innovations have underpinned economies of scale and embedded shipping into logistics systems of increasing complexity and reach. These developments have facilitated the creation of global value chains (Sturgeon et al., 2008; Coe and Yeung, 2015). Shipping, therefore, emerges both as a consequence of, and contributor to, the separation of production and consumption locations. Section 5 concludes that underlying shifts in production and consumption are likely to be more significant than carbon reduction measures which might reduce the environmental impact of shipping.

2. Theoretical background: socio-technical transitions and shipping

Socio-technical transitions theory (Geels, 2002) posits the notion of an embedded regime in a state of dynamic equilibrium for any given ensemble of technologies and related practices. The socio-technical transitions literature has a concern with how, why and to what effect innovations permeate through society. The theory adopts what is termed a multi-level perspective where the socio-technical space is divided into three distinct levels: niche, regime and landscape (see Figure 1.). At the heart of this socio-technical analysis is the ‘regime’ level centred on key technologies, around which accrete a dynamically-stable aggregation of economic structures, organisations, governmental regulations and laws, governance, social practices, behaviours and beliefs, which collectively act to allow the reproduction of the embedded regime. In turn, external or ‘landscape’ conditions in the form of resource availability, cultural norms and other factors provide a contextual framework within which the embedded regime may expand and develop. At the micro-level there may be ‘niche’ or grassroots innovations that ultimately grow to displace an embedded regime and hence power another wave of accumulation around a new set of technologies (Kemp et al., 1998; Hargreaves et al., 2013). Geels and Schot (2007) have further postulated a range of transition ‘pathways’ along which change may happen. As Turnheim et al. (2015) explain, the scope for different pathways crucially depends upon governance structures in place: where such structures are weak the available pathways and the pressure for change are more limited.

Figure 1. The multi-level perspective of socio-technical transitions applied to shipping.



2.1 Regimes, landscapes and niche emergence and shipping

Transitions theory is a way of understanding the permeation of socio-technical change across time and space. The socio-technical transitions literature tends to focus on niche emergence, and regime displacement or stability in the face of new technologies, consumer attitudes and related market matters (Wells and Nieuwenhuis, 2012; Xenias and Whitmarsh, 2013), and hence generally has a sector or single regime focus - although some studies have sought to understand and explain inter-regime relations (Sutherland, et al. 2015) in a manner that echoes nascent analyses of the food-water-energy nexus (Al-Ansari et al., 2015). Increasingly, interest in socio-technical transitions is concerned with the analysis or stimulation of structural shifts towards improved sustainability (Moss, 2009; Markard et al., 2012). While energy systems have been a core area of interest in this regard (Vasseur and Kemp, 2011; Von Bock und Polach et al., 2015), transport has also been considered (Nykvist and Whitmarsh, 2008; Whitmarsh, 2012; Geels, 2012). While in shipping the impact on adjacent 'regimes' is modest, the position of shipping within global production and consumption systems is crucial.

'Niches' are generally thought of as technological developments or spatially-constrained protected spaces within which experimentation takes place (Coenen et al., 2010). Again, the implications for such developments to impact the shipping socio-technical 'regime' are currently very limited. Sometimes, assumptions of the need for niche protection do not hold as Wells and Lin (2015) have demonstrated for the 'spontaneous emergence' of electric bicycles in China - but this exception may be hypothesised to arise in part because of the relatively low capital cost of the technology concerned, and the extremely modest infrastructure requirements. In personal transport modes, so-called 'early adopters' face modest costs and risks (Dill and Rose, 2012) though for larger vehicles such as cars other barriers emerge as a concern (Sovacool and Hirsh, 2009).

In contrast, technologies that require large capital investments and associated infrastructures, such as shipping, may be hypothesised to be ‘strongly embedded’ and thus have greater path dependency. This embedding is part of the process of ‘regime’ formation as described in the case of shipping by Geels (2002). That is to say, the emergence of key technologies such as steam power and iron hulls helped to elevate the economic significance of shipping and the size of vessels in such a manner as to demand greater landside investments, larger shipbuilding companies with capital and technical resources, and of course large shipping companies. Thus the economy as a whole became more dependent upon the shipping regime, and powerful vested interests aggregated around the ‘regime’. Such dependencies have been shown to be significant as barriers to change in other transport segments (Cowan and Hulten, 1996). As a consequence, the approach of strategic ‘niche’ management, to nurture emergent alternative technologies as proposed by Kemp et al. (1998) may not be viable.

Xu et al. (2015) portray shipping as evolving alongside the development of trade and the elaboration of commodity chains. Shipping therefore is the tangible expression of global production systems. It can therefore be concluded that it is the over-arching changes at a ‘landscape’ level that are likely to have the biggest impact on the future environmental performance of shipping, as is evidenced by, for example, air transport (Chèze et al., 2013). The major commodity flows e.g. oil, bulk materials and foods, containerised products, cars etc. at an inter-continental level are crucially determined by the myriad location decisions of producers and the continued possibilities of trade liberalisation. Interestingly, from a policy perspective it suggests that rather than seeking to tackle the mobility concerns of shipping with maritime policies, there is more traction to be gained from addressing the continued spatial separation of supply and demand.

Köhler (2014) argues that the ‘business as normal’ future may be challenged as one of three possible socio-technical pathways with regard to international transport. These are characterised as: further participation in global production and consumption networks via telecommunications technologies; the growth of 'fair trade' social movements that prioritise sustainable development; and a shift away from global integration by newly industrialising countries to enable local sustainable development. The latter pathway is of particular interest as it would begin to de-couple economic growth from world trade.

A more pressing concern is that of the pace of change. The contemporary pattern of production and consumption that is supported by, and supports, global shipping has taken decades to emerge and presumably would take many years to reverse. It is not readily apparent that such temporal generosity is available with regard to the impending breach of 'viable' carbon concentrations in the atmosphere and the prospect of non-linear climate change. As other aspects of modern materialist lifestyles are subject to multiple improvement measures, it is likely that ever-greater attention will be directed at shipping. For example, Eco-ships will play a small part in the changes that are likely to follow but are unlikely to be part of an overall 'regime' shift that is necessary, or that the socio-technical system of international maritime logistics requires in order to become more sustainable.

Therefore, in the case of shipping, there is a strong justification for considering contextual or landscape framing events as significant for the future sustainability of the industry. This is because, in terms of the technologies of shipping, the assets tend to be very enduring. In addition, in terms of the economic rationality of shipping the key demand factors are also very enduring and arise out of structural investments in production systems that are not readily adjusted. 'Landscape' changes include, for example, structural shifts in production and consumption locations at a global and regional scale; changes to fundamental input prices, notably petroleum; the opening or closing of significant shipping routes such as the Northern Sea Route in the Arctic (Georgescu, 2014; Liu and Kronback, 2010) or the Nicaraguan Canal linking the Caribbean Sea to the Pacific Ocean (). Major individual events can also be relevant at a ‘landscape’ level: for example the sinking and subsequent petroleum loss from major vessels such as the Torrey Canyon in 1967, and later the Exxon Valdez, prompted the shift into twin-hull designs for very large crude carriers (Scott Brown and Savage, 2006)

2.2 Eco-efficiency:’ regime’ deepening or ‘regime’ displacing?

An important strand in transitions thinking relates to the question of eco-efficiency whereby improved production processes create less environmental burden per unit of output. (Geels et al., 2015) Critics have argued that eco-efficiency fails to deliver substantive sustainability; and that only radical reform in terms of de-growth will achieve enduring change (Kallis et al., 2012). The critique of eco-efficiency has gained force over time, in part because of continued global pollution, resource consumption and increasing carbon emissions.

Eco-ships are generally referred to as a new generation of vessels that, compared with existing designs are more fuel efficient, through the process of hull design, engine design and the use of new technologies and materials, that is they are considered to be more ‘eco-friendly’ (Roussanoglou, 2013). Eco-efficiency in shipping has become an important theme in research and practice over recent years, with both technological and operational innovations getting attention (Lam and Lai, 2015). Eco-efficiency measures can be broadly divided into operational and technological innovations that contribute to a reduction in the environmental load per unit of a particular practice, service or product. It is important to note that in some instances, reductions in such environmental loads for one parameter (say CO_2) can increase loads for another (say freshwater toxicity). Taking a broader ‘transport’ perspective Beltrán-Esteve and Picazo-Tadeo (2015) conclude that the adoption of global best-practice eco-efficiency technologies has contributed to a significant improvement in environmental performance since the 1990s. However, it is not clear how much of the improvement observed is attributable to shipping, but, given that the long service life of ships and that the process of fleet renewal is extremely protracted, continuing fleet expansion may erode any gains made.

Recently, shipping eco-efficiency has been given greater attention (Lai et al., 2011; Lun et al., 2014). Two of the most obvious eco-efficiency operational measures are slow-steaming and cold ironing. Slow-steaming depends upon wider operational contexts such as capacity and the willingness of customers to accept strategies like virtual port arrival, but is rapidly becoming the norm (Psaraftis and Kontovas, 2013). Cold ironing (Alternative Marine Power) provides electrical power to a ship at berth allowing both main and auxiliary engines to be shut down and thus mitigating harmful emissions by allowing a vessel to connect to shore based sources of power, which should, in theory, create fewer harmful emissions. The practice of Alternative Marine Power for berthing vessels can offer significant reductions ($\geq$50% in CO_2, SO_4, NOx, PM) depending on the case in point. (Zis et al., 2014).

However, the gains of eco-efficiency may be offset by what is termed the 'rebound' effect. This effect can be traced back to the work of the British economist William Jevons who, in 1865, proposed that the paradoxical impact of the invention of a more efficient coal-powered steam engine would be to increase the demand for coal in aggregate, even though in individual applications the coal demanded would fall (Jevons, 1865). Put more broadly, gains in energy efficiency do not necessarily lead to equivalent reductions in energy use. In the realm of transport technologies, gains in energy efficiency at the level of an individual item of technology (a car, a truck, a ship) may result in two rebound outcomes: the use of that individual item may increase with say higher speed or longer distances travelled; and the increase in overall demand for the technology may overwhelm the displacement of less efficient versions from the stock of vehicles or vessels in use. Put another way, eco-efficiency measures may enable shipping operators, particularly those with large fleets moving high tonnages and volumes, to lower costs, and hence increase the demand for more efficient vessels, thereby increasing aggregate shipping use and the associated emissions.

2.3 Governance and policy

Governance intervention may be fundamental to socio-technical transition (Späth and Rohracher, 2012; Bäckstrand and Kronsell, 2015), including fiscal and other incentives, learning from socio-technical experimentation, consensus building, Research and Development support, infrastructure development, regulatory frameworks and other features (Beck et al., 2013; Small, 2012). Governance is a broadly defined concept comprising both formal and informal regulatory control, the allocation of social resources towards the resolution of specific problems, and also the construction of accepted norms of behaviour and action. Regulatory control can itself be a stimulus to innovation (Makkonen and Repka, 2016). The policy prescriptions of socio-technical transitions can be summarised as 'shielding, nurturing and empowering' (Verhees et al., 2015) in order to allow innovative sustainable technologies to break out of their niches and become mainstream.

Alternatively, socio-technical disruptions can provide opportunities that can be exploited for policy purposes (Marsden and Docherty, 2013). However, achieving such interventions at a multi-national scale may be problematic, as the required agencies and authority may be weak or non-existent. It is unsurprising therefore that much research into socio-technical change draws on concepts of national technological innovation systems, and the significance of intermediaries as potential change agents (Negro and Hekkert, 2008; Hekkert and Negro, 2009). The spatial definition of technology innovation systems may fail to resonate with international corporate structures (Binz et al., 2014) that could be more significant (Köhler et al., 2013; Dodourova and Bevis, 2014). Moreover, while, for example, Geels (2014) has sought to introduce power and politics into an understanding of regime resistance to change in the context of energy systems, there is a 'bounded' arena for their study of in the form of the national state and European Union. However, such a naturally bounded arena does not apply to global shipping (Lister, 2015) which operates in a multi-national context.

It can be argued that shipping operates within a regulatory and governance framework that exhibits unique characteristics (van Tatenhove, 2015; Lun et al., 2015). There is debate over the extent to which, in the absence of effective state or multinational governance mechanisms, 'private' maritime governance in the form of eco-ships or operational innovations can beneficially contribute (Lister, 2015). As Peters (2014) argues '…the immobilisation of the undesirable mobilities of ships and boats is inherently difficult at sea' and a similar case can be made with respect to the achievement of sustainability goals. In the case of shipping, inter-national (and international) governance may thus be a crucial issue - though Köhler (2014) argues international transport remains on the fringes of the environment and development policy fields. Multiple actors and agencies can be involved in governance, and in the case of shipping the governance 'map' is complex at both global and regional scales (Stokke, 2013). As Hackmann (2012) demonstrates, this complexity and attendant fragmentation has, as a consequence, meant that greenhouse gas emissions from shipping remain unregulated under the Kyoto Protocol or any other legally-binding international agreement. Indeed, according to Gritsenko and Yliskylä-Peuralaht (2013), even in the case of a single issue (SOx emissions) and a constrained area of action (the Baltic) the 'polycentricity' in shipping governance results in significant governance differences at the regional and local scales.

To date, policy measures appear to have a limited traction on shipping sustainability issues beyond some local benefits. The creation of zones such as the European Union Sulphur Emissions Control Area can have a significant impact on toxic emissions, but rather less so on greenhouse gases (Kalli et al., 2013). As Endresen et al. (2010) observe with their modelling, regulations and measures to abate emissions will be outweighed by an increase in traffic, resulting in a global increase in emissions. Further, Fagerholt et al. (2015) argue that with Emissions Control Areas ships may compensate by going faster outside the areas or taking longer (avoiding) routes, resulting in net increases in CO_2 emissions.

Governance can also be achieved in contractual and relational forms, a feature of some relevance to the position of shipping in global supply chains. As Cao and Lumineau (2015) observe, the success of such governance is strongly conditioned by the institutional context within which these relations are entered into: Conceptually at least shipping does not appear to be within a supportive institutional context. It is not surprising therefore that Lister (2015) argues that ‘private environmental governance’ is at best problematic. Indeed the combined failure of public and private governance in shipping has long been recognised as an issue (Yliskylä-Peuralahti and Gritsenko, 2014; Lister et al., 2015), which points to the intractability of the problems in this case.

A new concept introduced for new builds in shipping is the Energy Efficiency Design Index (EEDI). The International Maritime Organization (IMO) has set the standards for EEDI (Chestney, 2011). Further, a Ship Energy Efficiency Management Plan (EEMP) will have to be implemented for all ships. The purpose of the EEMP, among others, is to assist operators of old/existing vessels to improve the energy efficiency of their ships (IMO, 2011b). The main items in MARPOL Annex VI are shown in Tables 1 and 2.

According to Regulation 13 of MARPOL Annex VI the specifications of the new built eco-ships have to meet stringent requirements with regards to GHG emissions. Further, the new engines have to be designed to consume low-sulphur fuel oils to comply with the Annex VI requirements, which not only means ships need to be operated more efficiently, but also to be designed to be able to switch to low-sulphur fuel or even liquefied natural gas (LNG) when entering ECAs.

Table 1. MARPOL Annex VI – Emission Control Areas

SOx Content Outside ECA Areas	SOx Content Inside ECA Areas
4.50% m/m before 1 January 2012	1.50% m/m before 1 July 2010
3.50% m/m after 1 January 2012	1.00% m/m after 1 July 2010
0.50% m/m after 1 January 2020	0.10% m/m after 1 January 2015

Source: IMO, 2015a

Table 2. MARPOL Annex VI – NOx Emission Regulations

Tier	Ship Construction Date on or After	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	130 ≤ n ≤ 2000	n ≥ 2000
Tier I	1 January 2000	17.0	45.n-0.2	9.8
Tier II	1 January 2011	14.4	44.n-0.23	7.7
Tier III	1 January 2016	3.4	9.n-0.2	2.0

Source: IMO, 2011c

To invest in newbuilds or retrofit existing vessels, ship-owners would naturally make a decision based on the generated returns of different options (Olsen, 2014). The shipping industry has divided opinions over this issue. Eco-ships have received global recognition and support from various stakeholders including ship-owners, port facilitators and financiers such as banks. The financial benefits of reduced fuel (bunker) consumption were obvious but following the falls in bunker prices between 2009 and 2016, savings on bunker consumption although significant, were not as great as originally expected (see, for example, Anon., 2015). Moreover, with tightening environmental regulations, "greening" activities have become more generally required, fostering shipping companies, ship yards, port operators and ship investors engaging in a "paradigm shift" in operating and thinking. With 'eco-ships being the new ships' in the future, there are suspicions that no yard would sell non-eco-ships at this stage, and even that no one would be likely to order a non-eco ’ship’ in the future (Lloyd’s List, 2015). Port operators and ship investors have also been facilitating the transition. The Norwegian government launched a green shipping programme in 2015 which includes various green vessel and green port projects (The Maritime Executive, 2015). Since 2014, several ports, including Port Metro Vancouver, began to use GHG emission ratings to offer financial incentives to attract more efficient vessels to enter their ports. Leading banks in the shipping industry claim to use vessel efficiency rankings in making investment and financing decisions (World Maritime News, 2015).

On the other hand, eco-ships have received much criticism. Many in the industry believe eco designs are “old technology dressed up as new” (Anon., 2013). It is also debatable whether ‘eco’ is referred to as ecological or economical. Olsen (2014) examined the economic benefit of new eco-design vessels through comparing the net present value (NPV) of the eco and standard vessels. The results show that standard vessel’s speed flexibility outperforms eco-vessels’ lower fuel consumption, hence it achieves a higher NPV. On a technical level, some ship-owners also argue that the investment in newbuilds makes little economic sense and retrofitting existing ships is better (Lloyd’s List 2013).

Further, there is potentially a two-tier shipping market emerging, with fuel-efficient ships on the one hand and inefficient ones on the other (Haider et al, 2014). Since eco-ships are expected to be almost 30% more fuel efficient, the result could be that vessels that used to be considered as efficient will then be, *ceteris paribus*, less efficient and thus on the weak side of a two-tier shipping market. Carsten Wiebers, Global Head of Maritime Industries, KfW IPEX-Bank, said. ”We see a clear trend towards a two-tier market of high- and low-efficiency vessels - more energy efficient vessels have an enhanced marketability as well as a higher revenue potential for the ship owner and thus a more favourable risk profile for financiers.” (World Maritime

News, 2015, online). Overall therefore, in trying to achieve sustainable socio-technical transition governance will therefore be the means by which (beyond mere market forces) shipping companies may be encouraged, or possibly compelled, to adopt technologies which generate lower emissions or practices which result in overall lower emissions.

3. Methodology

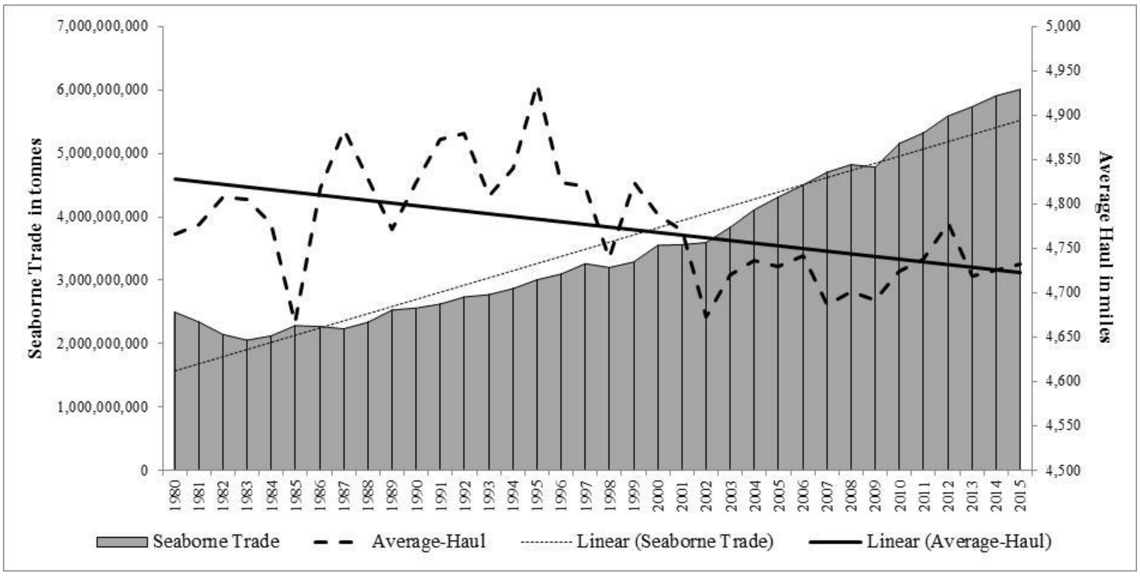
A substantial body of research already exists to attest to the myriad sustainability issues that shipping faces (Lai et al., 2011). While the focus in this paper is primarily on carbon emissions it is recognised that other concerns include toxic emissions, operational and accidental pollution, waste discharges, ballast water contamination, ship dismantling practices, and noise.

3.1. Shipping CO_2 emissions: the aggregate position

In order to understand how shipping is following embedded path dependency and how shipping CO_2 emissions have grown over time this section demonstrates, using a top-down data analysis the overarching problems facing the industry. As Eyring et al. (2010) demonstrate, nearly 70% of ship emissions occur within 400 km of coastlines; and emissions in ports are a major concern (Maragkogianni and Papaefthimiou, 2015; Zis et al., 2014). Further, the regional and local distribution of negative environmental impacts from shipping is highly variable depending upon location, port characteristics, and the type of shipping involved (Dalsøren et al., 2009).

The underlying cause of sea transport emissions is the burning of heavy-fuel oil and with emission levels that are influenced by cargo parcel size, type of vessel and operation modes. It is argued in the literature that ships are a significant source of pollution per tonne of fuel burned and that fuel consumed by ships accounts for 10% to 20% of world consumption and for 20% to 30% of global emissions (Corbett et al., 1999; Deniz et al., 2010). The demand for sea-transport (seaborne trade demand) is generally expressed in tonne-miles to reflect the time a ship completes a voyage and measured by multiplying the amount of transported cargo (in tonnes) by the average distance (in miles); this distance effect is referred to as the average-haul (Stopford, 2009). Figure 2 compares growth of seaborne trade (year-on-year) with average-haul over which each tonne of cargo is transported, which illustrates that the overall trend of seaborne trade continues to increase while the overall trend for average haul continues to decrease. The overall energy efficiency of the shipping industry continues to improve, reducing the amount of emissions per tonne of transported cargo by sea. However, total marine fuel consumption continues to increase due to increase in demand for capacity.

Figure 2. Developments in bulk seaborne trade (tonnes) vs. Average-Haul (miles)



Note: Figure 2 illustrates and compares developments in seaborne-trade trend with changes in shipping average haul over-time. The left vertical axes represent seaborne trade in tonnes and the right vertical axes represents shipping average haul in miles.

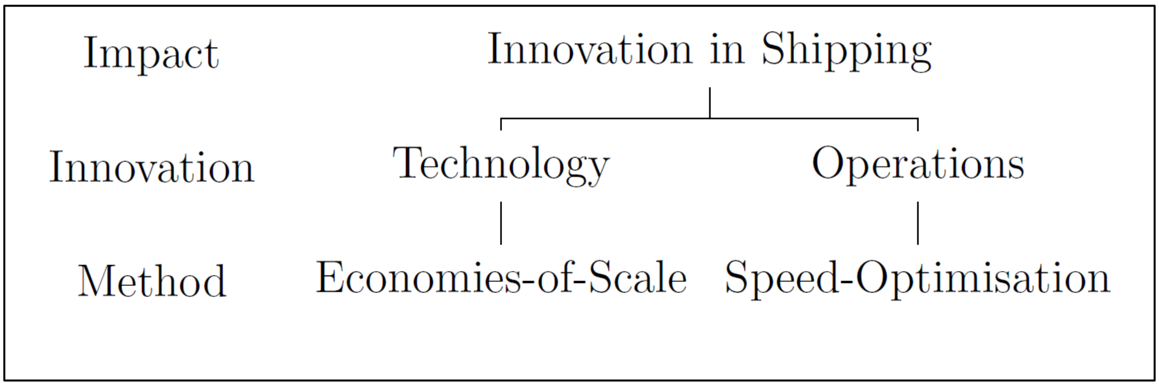
Note: Seaborne-trade estimate in this paper is based on oil (crude and products) and major bulk (Iron-ore, Coal, Grain, Bauxite Alumina and Phosphate Rock) trades and excludes steel production, forest production, containers, LPG, LNG, Chemical and other dry bulk.

Source: calculated by authors

3.2. Shipping Fuel Consumption and Carbon Emissions Estimates

As the objective of this paper is to investigate the impact of innovation in shipping on reducing global shipping emissions, the impact of different sizes of ships at different steaming speeds on shipping emissions are assessed. This is simply because the literature considers economies of scale and speed optimisation as the most important types of technological and operational innovations, respectively. Hence, some studies investigate the impact of economies of scale on shipping emissions (see Lindstad et al., 2012 and references within) and others focus on the impact of steaming speed on shipping emissions (see Corbet et al., 2009 and Lindstad et al., 2011). Figure 3 depicts the philosophy of the approach in this study.

Figure 3. The philosophy of the approach



Two approaches are recommended in the literature to estimate global shipping emissions. A fuel-based (top-down) method that is suitable for macro-level analysis and an activity-based (bottom-up) method that is suitable for micro-level analysis (for details see Chang *et al.*, 2014 and references within). The bottom-up approach is the most accurate method to estimate marine vessels emissions (Ng *et al.*, 2013); however, this approach is more applicable for studies that focus on specific areas where data for vessel particulars are easier to quantify, for example Chang et al. (2014) measure emissions within the port of Incheon, Korea, for different types of vessels from arrival to departure, and Ng *et al*. (2013) measure emissions within Hong Kong and the Pearl River Delta. This is contrary to this paper's objective, which is to investigate the impact of technological and operational innovations on global shipping emissions. Our focus is on higher hierarchy data levels and not lower hierarchy levels, so a top-down fuel-based approach is the most suitable and appropriate method to address the long-run relationships between shipping macroeconomic variables such as average haul and seaborne trade, and global shipping emissions. Thus, the framework consists of three steps. First, estimate daily bunker consumption per tonne of transported cargo. Second, estimate annual seaborne trade and hence annual bunker consumption for seaborne trade. Finally, using constant emission factors we estimate annual shipping emissions from global seaborne trade.

This study also employs a top-down method to estimate shipping emissions because it is the best fit for the research objective, and to compensate for the absence of global shipping activity data. Seaborne trade activities for oil (crude and product) and major bulk trades (iron ore, coal, grain, bauxite alumina, phosphate rock) are good proxies for general shipping as they account for 72% of global seaborne trade (Clarksons, 2016)[1], although it is recognised that different categories of shipping will have different outcomes in detail.

Clarksons Shipping Intelligence Network (2016), reports annual data for seaborne trade demand ($\mathrm{STD_t}$) in tonne miles, and this estimate accounts for average transported distance for each tonne of cargo, thus, the following equation is used to estimate annual Average haul (Ah) in miles.

$$\mathrm{Ah}_t(\mathrm{Miles}) = \frac{\mathrm{STD}_t\ (\mathrm{Tonne{-}Miles})}{\mathrm{ST}_t\ (\mathrm{Tonne})} \tag{1}$$

[1] Seaborne trade and tonne-mile tables. Clarksons is the SIN: shipping intelligence network, https://sin.clarksons.net/

To put this in context, in 2012 demand for seaborne trade was estimated to be 22,356 (STD_t) billion tonne miles, meaning that a total of 4,099 (ST_t) million tonnes of cargo has been transported by sea for an average distance of 5454 (Ah_t) miles. Table 3 and Figure 4 (Panels *b* and *c*) report on daily fuel consumption categorised by different steaming speed levels, different vessel ages, for different cargo capacity sizes and for both oil tankers and major bulk carriers.

Table 3: Daily averages of vessels' fuel consumption categorised by speed and cargo capacity.

Tankers	*Vessels age range in years (0-20)*		
Dwt Range	*Sp*	*Cons*	*Dwt*
10 - 19,999	**13.8**	**19.3**	**15,021**
20 - 29,999	**14.9**	**27.4**	**25,435**
30 - 44,999	**14.8**	**31.4**	**37,844**
45 - 59,999	**14.8**	**32.4**	**48,387**
60 - 79,999	**14.9**	**41.5**	**72,407**
80 - 119,999	**14.9**	**49.2**	**107,738**
120 - 199,999	**15.2**	**64.8**	**154,944**
200 - 319,999	**15.7**	**92.8**	**305,724**
320,000 +	**16.3**	**111.0**	**325,498**
Total Avg.	**14.7**	**41.4**	**85,941**

Bulkers	*Vessels age range in years (0-20)*		
Dwt Range	*Sp*	*Cons*	*Dwt*
10 - 19,999	**13.3**	**17.9**	**15,084**
20 - 24,999	**13.6**	**20.8**	**22,873**
25 - 29,999	**13.9**	**22.4**	**27,943**
30 - 39,999	**14.1**	**26.5**	**34,708**
40 - 49,999	**14.2**	**28.9**	**45,672**
50 - 59,999	**14.3**	**31.5**	**56,248**
60 - 79,999	**14.2**	**33.3**	**74,219**
80 - 99,999	**14.3**	**38.0**	**85,854**
100 - 119,999	**14.6**	**47.0**	**112,619**
120 - 159,999	**14.1**	**47.4**	**148,755**
160,000+	**14.8**	**61.8**	**197,570**
Total Avg.	**14.2**	**33.4**	**73,306**

Note 1: Table 3 reports data for vessels' specifics that are used to estimate shipping emissions. In both tables, for tankers and bulkers, the columns from left to right represent vessel capacity, vessel speed, vessel daily consumption and average cargo capacity.

Note 2: For full dataset see Appendix 1.

Note 3: estimates calculated by authors based on data collated from Clarksons Shipping Intelligence Network

Abbreviations: Sp - speed; Cons – Fuel Consumption; Dwt – Deadweight Tonnes; Avg. – Average

Source: Clarksons Shipping Intelligence Network

The daily amount of burned fuel per tonne of transported cargo (Bf_{daily}^{tonne}) is estimated by dividing daily average bunker consumed (Bf_{daily}) by the average cargo capacity (Ac) using the following formula:

$$Bf_{daily}^{tonne} = \frac{Bf_{daily}}{Ac} \quad (2)$$

Thus, average bunker per annum consumed for a specific trade is estimated using the following formula:

$$Bf_{annual_t} = Bf_{daily_t}^{tonne} \times ST_{annual_t} \quad (3)$$

Shipping emissions are then estimated for annual seaborne trade ($EmST_{i,annual_t}$) by multiplying average consumed bunker per annum for a specific trade (vessel type) by the appropriate emission factor (Ef_i) using the following formula:

$$EmST_{i,annual_t} = Bf_{annual_t} \times Ef_i \quad (4)$$

Annual shipping emissions for oil and major bulk trades are estimated and illustrated in tonnes per annum in Panel A of Figure 4, and reported in Table 4 along with emission factors for different types of emissions ($NO_x, SO_2, CO_2, HC, PM, SFC$), in g/kwh and (%) of m/m.

Table 4. Average annual shipping emissions

Trade (Type of Ship)	Oil Trades (Tanker)			Major Bulk Trades (Bulker)		
Emission Type	Ef (g/kwh)	AE (g/kwh)	% AE	Ef (g/kwh)	AE (g/kwh)	% AE
NO_x	14.8	773	1.6%	16.2	201	1.8%
SO_2	11.7	611	1.3%	10.9	158	1.2%
CO_2	690	**36,015**	**73.8%**	649	**9,339**	**73.6%**
HC	0.5	26	0.1%	0.54	7	0.1%
PM	1.43	75	0.2%	1.28	19	0.1%
SFC	217	**11,327**	**23.2%**	204	**2,937**	**23.1%**

Source: estimated by authors using Ef data reported in Deniz et al, 2010.

Note: Table 4 reports emission factors and average annual emissions for tankers and bulkers. Values are reported for type of emission in grams per kilowatt-hour (g/kwh) of energy generated.

Abbreviations: Ef: - emission factor; AE: - average annual emissions; % AE - percentage of average annual emissions

* *Calculations for annual emissions for tanker are based on averages of steaming speed from 13.8 to 16.3 Knots, Daily consumption from 19.3 to 111.0 tonnes and average transported cargo capacity from 15,021 to 325,498 DWT.*

*** Calculations for annual emissions for bulkers are based on overall averages of steaming speed from 13.3 to 14.8 Knots, Daily consumption from 17.9 to 61.8 tonnes and average transported cargo capacity from 15,084 to 197,570 DWT.*

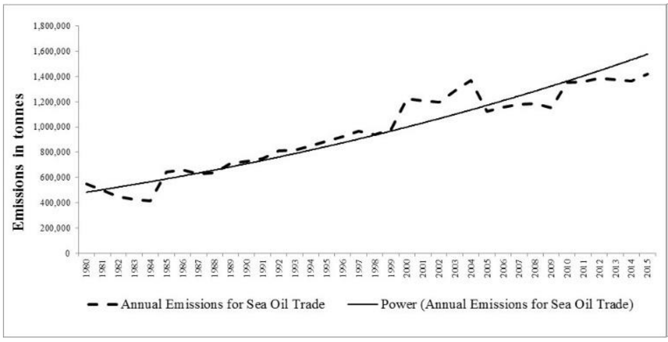
It is clear from these estimates that there have been significant increases in overall sea transport emissions. This can largely be attributed to the upsurge in demand for seaborne trade discussed earlier and the maximising of steaming speeds during inelastic supply periods. Figure 4 (Panel A) illustrates the continuous increase in annual emissions over the last four decades which has occurred from transporting crude oil and major bulks by sea. The vertical axis represents the estimate of total shipping emissions in tonnes.

The left hand side of Panel A represents annual emissions for oil trades while the right hand side represents annual emissions for major bulk trades. Panel B illustrates the impact of ships' different cargo capacity and different speed levels on bunker consumption for tanker and bulker vessels. The horizontal axis represents different levels of daily bunker consumption. The right vertical axis represents speed in nautical miles per hour (Knots). The left vertical axis represents vessels' cargo capacity in deadweight tonnage (DWT). Panel C illustrates the impact of different steaming speeds levels on daily bunker consumption for tanker and bulker vessels. The horizontal axis represents different speed levels and the vertical axis represents average daily bunker consumption. It can clearly be seen from Figure 4 that the overall trends are all in an upward direction. Despite improvements in technology, ship size and the more efficient use of fuel, the fact remains that the scale of shipping capacity represented by the number of vessels remains a key consideration in any sustainable dynamic for the shipping industry.

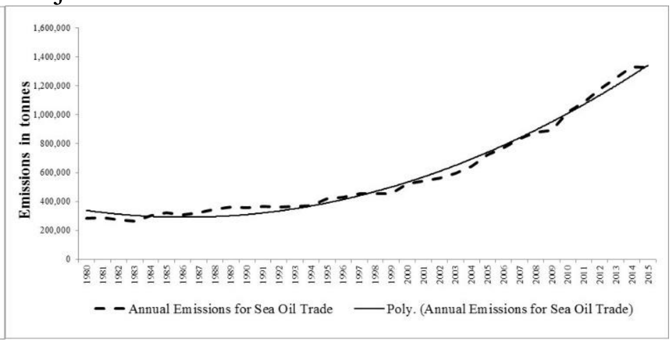
Figure 4. The impact of shipping capacity demand and speed on emissions

Panel A: Annual estimated shipping emissions

Oil Trades



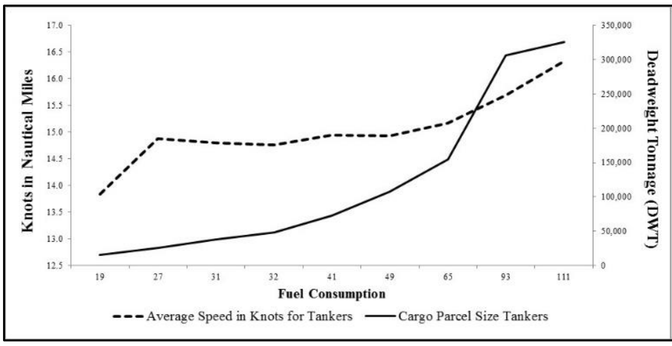
Major Bulk Trades



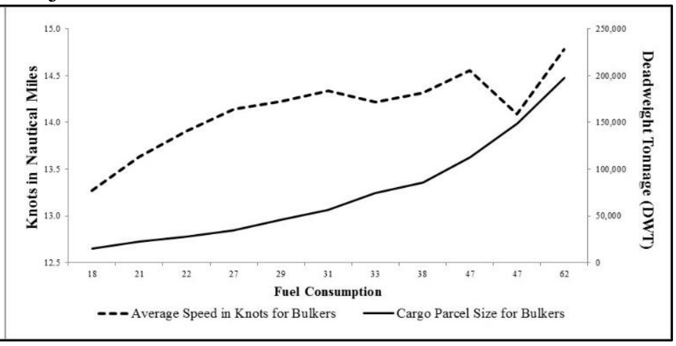
Source: Calculated by authors**.**

Panel B: The impact of ships' cargo capacity and speed on fuel consumption

Oil Trades



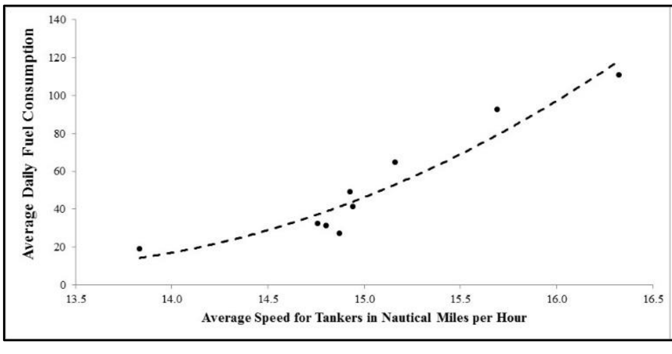
Major Bulk Trades



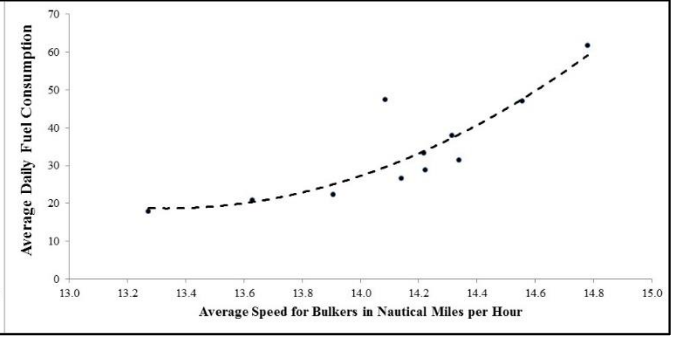
Source: Calculated by authors.

Panel C: Average Steaming Speed Vs. Daily bunker consumption for ships

Oil Trades



Major Bulk Trades



Source: Calculated by authors

In light of the earlier discussion regarding path dependency and fragmented governance in shipping, and the evidence provided above in respect of the growth in fuel consumption and carbon emissions the question that arises is; can shipping achieve a second socio-technical transition for carbon emissions reduction? in order to improve its sustainability.

4. Path dependency and 'regime' embedding in shipping

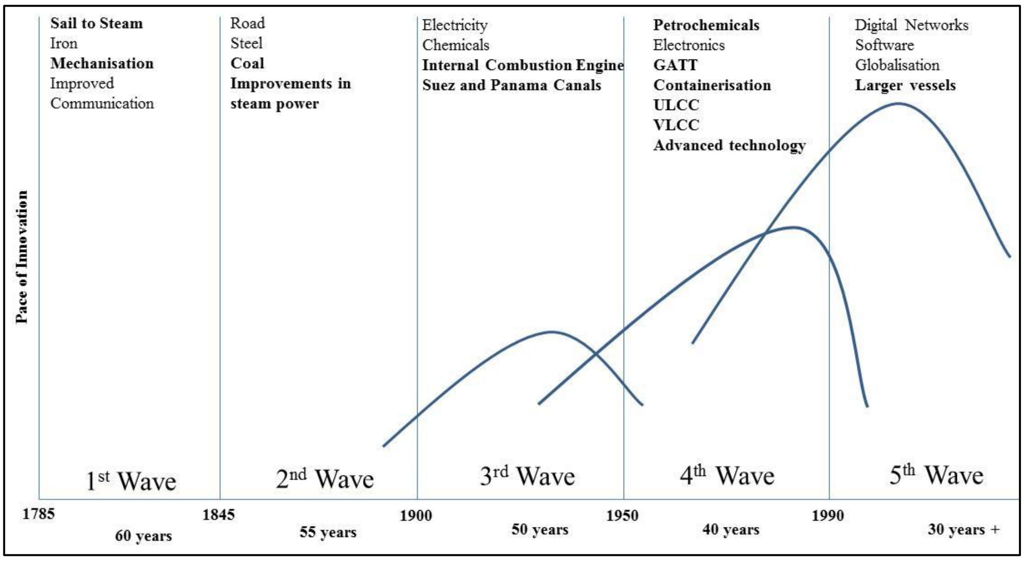
The scale of change in shipping has arguably been most dramatic over the last fifty to sixty years where technological developments have created an environment for those changes to have occurred which could not have happened in previous eras. Since the fifteenth century when global sea routes began to be developed, transport costs have generally fallen while trade volumes have increased, and thus it can be argued that as time has passed while the efficiency of shipping as a mode of transport has increased there has been a corresponding negative environmental impact due to the much greater number of ships being used (Stopford, 2009). The five 'waves' of innovation in shipping identified by Rodrigue and Notteboom (2015) and discussed below seek to build upon and elaborate more generalised long-wave theory as originated by Schumpeter (1934) and others. In terms of the ideas in socio-technical innovation theory, these long-waves can be understood as distinct eras or periods within the broader framework of the transition of shipping from sail and wooden hulls through to the modern era of diesel engines and steel hulls. From the perspective of this paper, each wave therefore represents a deepening of the overall significance of shipping as an activity.

Rodrigue and Notteboom (2015) identify five key phases of technological diffusion which have created economic growth opportunities, including for shipping. (Figure 5). The first wave (1785-1845) relied on innovations in areas such as water power, textiles and iron. Technological innovations in ship design and shipbuilding led to improved reliability. While motive power for ships still relied on wind and sail the shipping industry was robust enough to support commerce between the main economic powers. After the first trans-Atlantic iron-hull steamer the SS Great Britain (3,640 tons) was built in 1845 (Corlett, 1975) the scale of ships started to increase (Gibbs, 1957). Lucassen and Unger (2011) identify that maritime productivity was derived from a combination of best practice, and stronger economic leadership which included institutional changes, technical improvements, and economies of scale. Improvements in shipping generated commercial expansion by facilitating increased division of labour and production at a continental scale and as a consequence the overall costs of production and transport were significantly reduced.

The second wave (1845-1900) involved the use of coal through the development of the steam engine. This enabled larger steamships which increased the effectiveness of maritime transport and further enhanced global trade. The third wave (1900-1950) revolved around electrification and the development of internal combustion engines which improved the efficiency of shipping still further (Rodrigue and Notteboom, 2015). In the post-1945 environment the framework of sea trade began to change, influenced by post war reconstruction and the establishment of the United Nations (Stopford, 2009; Rodrigue and Notteboom, 2015).

The fourth wave (1950-1990) saw significant moves to develop a global free trade economy stimulated with the General Agreement on Tariffs and Trade (GATT) of 1948. During this period bulk carrier markets expanded, general cargo became increasingly containerised and specialist shipping operations developed. In the liquid bulk sector economies of scale dictated that it was better to ship large volumes of crude from production areas to refineries located closer to markets and this led to the development of ULCC and VLCC vessels (e.g., greater than 200,000 deadweight tons). Larger dry bulk vessels were also developed to deliver cargoes from production regions to processing facilities closer to final market. New ship types were developed to carry dry bulk, liquid bulk, oil and chemical products, vehicles and containers. Advances in cargo handling and shipboard technology helped reduce crew size and stevedoring labour. Additional developments in ship registration and the move from nation state flags to flags of convenience facilitated further cost reductions (Pettit and Bergantino, 1997; Stopford, 2009; Rodrigue and Notteboom, 2015).

Figure 5. Five waves of technological innovation and economic growth in shipping



Source: Adapted from: Hargroves and Smith (2005); Rodrigue and Notteboom (2015).

The fifth wave (1990 to the present) has seen rapid globalisation supported by the development of information systems allowing integrated production and distribution. Shipping empowered development by providing vessels of increasing size, and export-oriented economies benefited from the scale change in shipping to access global markets leading to sharp increases in maritime trade volumes. The preference of consumers for increasingly diverse products led to significant increases in trade volumes between Asia and Europe in this period (Estevadeordal, Frantz, and Taylor 2002). Sea transport has thus contributed to the development the global economy by providing access to and from other economies, its services and infrastructure have facilitated significant reductions in transport costs and management and operation of those services and infrastructure have supported cost minimisation (Rodrigue and Notteboom, 2015; Stopford, 2009).

Shipping enables trade; but developments in shipping may also increase or stimulate trade because new things become possible. Important factors have included the average size of merchant ships increasing substantially and increases in average operating speeds for merchant shipping with maximum possible speeds increasing from around 15 knots to 25 to 30 knots. Maritime freight traffic increased annually for many years and the amount of cargo transported by sea exceeded 8 billion tonnes for the first time in 2007. Global shipping capacity doubled between 1990 and 2014 (an average annual increase of over 4 per cent) and transport capacity also doubled in the same period to around 33 trillion tonne-miles (World Ocean Review, 2015).

Most of the global merchant fleet consists of five types of ships: general cargo vessels; oil tankers; bulk carriers; passenger liners; and container ships. By increasing both the scale and speed of cargo handling, further reductions in the costs per transported unit have been achieved. There are two principal sub-markets of shipping being bulk liquid cargoes such as oil and petroleum products accounting for around a quarter of all goods transported by sea, and dry bulk cargoes such as iron ore, coal, grain, phosphates and bauxite. Other dry cargo is known as general cargo and shipped on liner vessels mainly in containers. Standardisation, through the use of containers, led to many technical innovations and fundamental organisational change. Capital investment along the entire transport chain were necessary to ensure that containers were used efficiently, increasing capital intensity. Since 1985 global container shipping volumes have increased from 152 million tonnes loaded to 1.6 billion tonnes loaded in 2014 (UNCTAD, 2015). During the same period the containerised market share of total dry cargo transport rose from 7.4 per cent to 25 percent. A total of 171 million TEUs, were transported in 2014 a rise from around 50 million TEU in 1996. Annual percentage increases in container volumes have generally been above 5% since 1996 and have often exceeded 10% (UNCTAD, 2015).

Wu and Lin (2015) show that in the container fleets a combination of scale economies an increased ship size is the primary basis for increased productivity and reduced costs, but also resulted in greater over-capacity. This is echoed by Tran and Haasis (2015) who noted an increase in revenue arising, but not necessarily profitability. This long-run growth in ship size in particular has profound implications for ports, as an increasing number are stranded unable to handle the larger vessels (Cullinane and Khanna, 2000). Hence the container ship example illustrates a pattern of spatial concentration, economies of scale, ship size increases and 'reinforcing' landside developments that act to embed further the path dependency around the use of shipping to link production and consumption locations. Of course, as Zhang et al. (2015) illustrate for the case of Hong Kong, if global manufacturing businesses change locations (in this case away from the Chinese Pearl River Delta) then the port volumes will decline.

In parallel with the greater scale and lower costs of shipping, Kaukiainen (2014) draws attention to quality improvements such as greater reliability that substantially contributed to the robustness and hence attractiveness of long-haul shipping. Ekberg and Lange (2014) go further, to argue that maritime innovations in organisation, operations and technology played a critical role in stimulating (rather than simply enabling) globalisation by creating the right preconditions, a view with which Levinson (2010) concurs with regard to containerisation. Such is the embedded nature of liner shipping that approximately 60 percent of the value of seaborne trade is now moved in containerised form and the capital investment required to support the industry has resulted in more enduring physical infrastructures (World Shipping Council 2016, UNCTAD, 2015).

5. Conclusions

Socio-technical transitions theory posits change as occurring (or not) as a consequence of multiple causal agents including the actions of key individuals within institutional and structural settings. As shown above, shipping has gone through various phases arising out of the interplay of such causal agents that constitute the landscape, regime and niche levels. While Rodrigue and Notteboom (2015) identify five phases of development to which shipping clearly relate, a socio-technical transition to sustainability would constitute a 6th phase of development and it is clear that pressures are emerging which may lead to such a new phase of development.

Despite improvements in technology, ship size and the more efficient use of fuel, the fact remains that the scale of shipping capacity, represented by the number of vessels, remains a key consideration in any sustainable dynamic for the shipping industry. This brings into the debate the discussion which revolves around the development of eco-efficiency in shipping. Wuisan et al. (2012) frame eco-ship initiatives such as the Clean Shipping Project as instances of private governance, but also observe that market forces tend to undermine such efforts. Similar comments could be made with respect to the Maersk efforts with their 'Daily Maersk' business model that sought a premium for a high reliability service (Zhang and Lam, 2015). The question therefore arises as to whether or not the development of new classes of eco-ship can redress what has been an increasing trend in annual ship emissions over a very long period of time. Tracing the impact of eco-efficiency in terms of direct and indirect effects is a contentious and problematic area but the evidence presented in section four suggests that for the classes of shipping examined there has been long-run growth in both the volume of shipping and of emissions that would appear to be substantially greater than any eco-efficiency gains. Private governance is weak in shipping because of structural issues in the industry, with a generalised over-capacity acting to exert a downward pressure on prices and a resistance to the development of ‘premium’ green shipping offers. Collective governance of the shipping industry by individual nation states or combinations of states has also been relatively weak historically, with shipping as an inherently international business that mostly occurs outside national boundaries: shipping emissions are not therefore in the national carbon emissions accounts and do not feature in global compacts to limit carbon emissions. While the WMO has acted as an important organisational innovation with the credibility of the UN, it is constrained by the inability to enforce standards or to create really aggressive new requirements that might stimulate the sort of technological and operational innovations that have been evident in, for example, the car industry.

From a policy perspective, sustainability concerns with regard to shipping mirror those with regard to air travel: the lack of regulatory levers and technological opportunities seem to mean inevitable increases in environmental burdens unless volume growth can be constrained. Regulatory controls such as those developed for some European waters (e.g. the Sulphur Emission Control Areas) are clearly helpful in some regards, but will contribute little to carbon emission reductions.

Some landscape events, such as the opening up of a route in the Arctic, can be expected to stimulate further trade (Smith and Stephenson, 2013; Lindstad et al., 2016), as can deliberate attempts to increase commodity flows (Clott et al., 2015). Such comments apply to short-sea shipping equally (Morales-Fusco et al., 2012; 2013). Moreover, the long-run fall in petroleum prices since 2009 is hardly likely to restrict the growth in shipping generally. Structural changes in the industry, particularly around the consolidation of the industry and the emergence of global businesses able to orchestrate entire ‘end-to-end’ logistics solutions, are likely to reinforce the attractiveness of shipping and hence increase demand.

In turn, it can therefore be concluded that regime shifts, while enabled by technological innovation or alterations in behaviour at niche level, are powerfully shaped by landscape level pressures. The physical movement of materials and goods over long distances may in time be eroded by deliberate attempts to create spatially-bounded circular economies, but at present there is no evidence that efforts in this regard have had any meaningful impact on aggregate flows.

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Appendix 1

Bulkers

Age Range	*20 years plus*		*15-19 years*		*10-14 years*		*5-9 years*		*0-4 years*		*Average*		
Dwt Range	*Sp*	*Cons*	*Sp*	*Cons*	*Sp*	*Cons*	*Sp*	*Cons*	*Sp*	*Cons*	***Sp***	***Cons***	***Dwt***
10 - 19,999	13.5	18.5	13.4	17.5	13.1	16.7	12.8	17.2	13.5	18.5	**13.3**	**17.9**	**15,084**
20 - 24,999	13.6	20.2	14.1	21.2	14.1	23.3	13.1	20.5	13.1	18.5	**13.6**	**20.8**	**22,873**
25 - 29,999	13.8	21.9	14.0	22.7	14.0	23.2	13.8	22.6	14.0	22.0	**13.9**	**22.4**	**27,943**
30 - 39,999	14.1	29.0	14.1	26.9	14.3	26.2	14.1	25.4	14.1	26.0	**14.1**	**26.5**	**34,708**
40 - 49,999	14.1	27.5	14.3	29.2	14.5	31.5	14.6	30.3	13.6	25.0	**14.2**	**28.9**	**45,672**
50 - 59,999	14.2	33.1	14.9	39.1	14.4	30.0	14.3	31.5	14.3	31.7	**14.3**	**31.5**	**56,248**
60 - 79,999	14.0	32.0	14.1	32.4	14.3	34.0	14.4	34.3	14.3	34.4	**14.2**	**33.3**	**74,219**
80 - 99,999	14.0	43.0	14.2	41.3	14.6	40.8	14.3	38.0	14.3	37.4	**14.3**	**38.0**	**85,854**
100 - 119,999	14.7	44.0	-	-	15.0	59.0	13.7	39.5	14.6	47.2	**14.6**	**47.0**	**112,619**
120 - 159,999	13.9	46.0	14.3	48.8	14.7	57.0	14.6	0.0	15.0	-	**14.1**	**47.4**	**148,755**
160,000+	14.5	70.2	14.6	59.6	14.6	57.9	14.7	61.3	15.0	62.7	**14.8**	**61.8**	**197,570**
Total Avg.	**13.9**	**29.8**	**14.2**	**31.7**	**14.3**	**33.4**	**14.2**	**35.0**	**14.3**	**35.6**	**14.2**	**33.4**	**73,306**

Tankers

Age Range	*20 years plus*		*15-19 years*		*10-14 years*		*5-9 years*		*0-4 years*		*Average*		
Dwt Range	*Sp*	*Cons*	*Sp*	*Cons*	*Sp*	*Cons*	*Sp*	*Cons*	*Sp*	*Cons*	***Sp***	***Cons***	***Dwt***
10 - 19,999	13.7	18.9	13.7	18.8	14.2	21.1	13.8	19.3	13.8	19.2	**13.8**	**19.3**	**15,021**
20 - 29,999	14.7	25.8	15.2	26.8	15.0	29.9	14.9	29.5	15.0	29.7	**14.9**	**27.4**	**25,435**
30 - 44,999	15.0	30.1	14.9	35.0	14.7	29.7	14.8	30.3	14.7	36.2	**14.8**	**31.4**	**37,844**
45 - 59,999	14.2	30.5	14.7	33.6	14.8	33.2	14.9	31.8	14.6	33.1	**14.8**	**32.4**	**48,387**
60 - 79,999	14.3	35.2	14.4	42.4	15.1	41.6	14.9	42.1	15.2	41.4	**14.9**	**41.5**	**72,407**
80 - 119,999	14.7	44.1	14.7	46.8	14.9	50.6	15.1	50.7	14.9	50.3	**14.9**	**49.2**	**107,738**
120 - 199,999	14.7	65.7	14.7	62.5	15.1	64.6	15.4	66.4	15.2	67.4	**15.2**	**64.8**	**154,944**
200 - 319,999	14.9	77.5	15.4	88.8	15.8	89.6	15.7	99.0	15.8	98.8	**15.7**	**92.8**	**305,724**
320,000 +	0.0	0.0	0.0	0.0	16	137	16	105	16.7	105.4	**16.3**	**111.0**	**325,498**
Total Avg.	**14.4**	**29.6**	**14.6**	**42.8**	**14.9**	**50.0**	**14.7**	**39.6**	**14.8**	**44.8**	**14.7**	**41.4**	**85,941**

Note: Table 3 reports data for vessels' specifics that are used to estimate shipping emissions. In both tables, for tankers and bulkers, the columns from left to right represent vessel capacity, vessel speed, vessel daily consumption and average cargo capacity.

Abbreviations: Sp - speed; Cons – Fuel Consumption; Dwt – Deadweight Tonnes; Avg. – Average

Source: Data collated from Clarksons Shipping Intelligence Network